

**patent claims**

1. Method for qualifying a reflective optical element having a free interface at  
5 which radiation is reflected
- comprising the step of
- measuring at various wavelengths and/or various incidence angles of said  
10 radiation a reflectance and a photoelectron current induced by said radiation  
in an area of the free interface  
resulting in a reflectance curve as a function of wavelength and/or incidence  
angle  
wherein said reflectance curve has a wavelength region and/or incidence  
15 angle region of maximum reflectance  
and in a photoelectron current curve as a function of wavelength and/or  
incidence angle wherein said photoelectron current curve has a profile  
within said wavelength region and/or incidence angle region of maximum  
reflectance.
- 20
2. Method according to claim 1,
- further comprising the step of
- 25 determining the slope of said profile of the photoelectron current at the  
wavelength and/or incidence angle of maximum reflectance.
3. Method according to claim 1,
- 30 further comprising the step of
- determining a maximum or minimum of said profile of the photoelectron  
current curve within the wavelength region and/or incidence angle region of  
maximum reflectance, wherein the wavelength corresponding to the  
35 maximum or minimum of said profile of the photoelectron current curve is

closest to the wavelength corresponding to the maximum of the reflectance curve.

4. Method according to one of the claims 1 to 3, wherein the wavelength of the radiation lies in the EUV range.

5. Method for operating a reflective optical element, wherein the reflective optical element comprises a cap layer system

comprising the step of

qualifying the reflective optical element according to claim 3 or 4.

6. Method according to claim 5, wherein the partial pressures of a residual gas atmosphere around the reflective optical element are readjusted in such a way that the wavelength corresponding to the maximum of the profile of the photoelectron current curve is about equal to the wavelength corresponding to the maximum of the reflectance curve.

7. Method for determining a thickness profile of a multilayer system and/or a cap layer system of an optical element having a free interface at which radiation is reflected

comprising the steps of

(i) measuring at various wavelengths and/or incidence angles of said radiation a reflectance and a photoelectron current induced by said radiation in an area of the free interface

resulting in a first reflectance curve as a function of wavelength and/or incidence angle

wherein said first reflectance curve has a wavelength region and/or incidence angle region of maximum reflectance

and in a first photoelectron current curve as a function of wavelength and/or incidence angle wherein said first photoelectron current curve has a profile within said wavelength region and/or incidence angle region of maximum reflectance;

(ii) comparing said first reflectance curve and/or said first profile with a second reflectance curve and/or a second photoelectron current curve, wherein said second reflectance curve and/or said second photoelectron current curve is obtained by a simulation for a given thickness of the layers of the multilayer system and/or of the layers of the cap layer system;

(iii) if said first reflectance curve and/or said first profile do not approximately coincide with said second reflectance curve and/or said second profile repeating step (ii) with a different thickness of the layers of the multilayer system and/or a different thickness of the layers of the cap layer system.

8. Method according to claim 7, wherein the wavelength of the radiation lies in the EUV range.

9. Method according to claim 7, wherein in step (ii) the first profile and/or the first reflectance curve are compared with reference data measured at a reflective optical element with a multilayer system and a cap layer system of known thickness instead of comparing with a second reflectance curve and/or a second photoelectron curve obtained by simulation.

10. Method according to one of the claims 1 to 9, wherein the photoelectron current curve and the reflectance curve are measured at several points on the interface in order to achieve spatial resolution.

11. Method for operating an EUV lithography apparatus comprising at least one optical element reflecting EUV radiation, wherein on top of said optical element a topmost cap layer is formed during irradiating operation due to contamination

comprising the step of

switching from irradiating operation to a detection mode, in which the thickness of said topmost cap layer is determined by a method according to one of the claims 7 to 10.

12. Method according to claim 11, wherein a residual gas atmosphere is modified in such a way, that the thickness of said topmost cap layer is reduced if contamination control parameters are exceeded.
- 5 13. Method according to claim 11, wherein a residual gas atmosphere and the cross section and/or position of an incident light beam are modified in such a way that material is deposited and/or removed at defined locations of the free interface of the reflective optical element, if contamination control parameters are exceeded.
- 10 14. A method for determining a phase shift of a standing electromagnetic wave in the extreme ultraviolet up to the soft x-ray wavelength region at the free interface of a multilayer system, comprising the steps of
- 15 illuminating the free interface of a multilayer system with radiation in the extreme ultraviolet up to the soft x-ray wavelength region;
- measuring the reflectance and the photoelectron current in a spectrally resolved fashion; and
- 20 determining the profile of the photoelectron current in the region of maximum reflectance, and ascertaining therefrom the phase shift of the standing electromagnetic wave at the free interface.
- 25 15. Method for determining a phase shift of a standing electromagnetic wave in the extreme ultraviolet up to the soft x-ray wavelength region at the free interface of a multilayer system, comprising the steps of
- illuminating the free interface of a multilayer system with radiation in the
- 30 extreme ultraviolet up to the soft x-ray wavelength region;
- measuring the reflectance and the photoelectron current in an angularly resolved fashion; and
- 35 determining the profile of the photoelectron current in the region of

maximum reflectance, and ascertaining therefrom the phase shift of the standing electromagnetic wave at the free interface.

5 16. A method for determining the phase shift of a standing electromagnetic wave in the extreme ultraviolet up to the soft x-ray wavelength region at the free interface of a multilayer system, having the steps of:

illuminating the free interface of a multilayer system with radiation in the extreme ultraviolet up to the soft x-ray wavelength region;

10 measuring the reflectance and the photoelectron current for a combination of wavelength and angular setting;

15 determining the profile of the photoelectron current in the region of maximum reflectance, and ascertaining therefrom the phase shift of the standing electromagnetic wave at the free interface.

20 17. A method for determining the thickness of a cap layer system on a multilayer system from the phase shift of a standing electromagnetic wave in the extreme ultraviolet up to the soft x-ray wave region at the free interface of a multilayer system, having a cap layer system, comprising the steps of:

illuminating the free interface of a multilayer system with radiation in the extreme ultraviolet up to the soft x-ray wavelength region;

25 measuring the reflectance and the photoelectron current in a spectrally resolved fashion;

30 determining the profile of the photoelectron current in the region of maximum reflectance, and ascertaining therefrom a first phase shift of the intensity of the standing electromagnetic wave forming at the free interface; and

35 comparing with an already known photoelectron current profile with reference to a second phase shift of the corresponding standing

electromagnetic wave at the free interface, and determining the difference in thickness by ascertaining the difference between the two phase shifts.

5 18. A method for determining the thickness of a cap layer system on the multilayer system from the phase shift of a standing electromagnetic wave in the extreme ultraviolet up to the soft x-ray wave region at the free interface of a multilayer system, having a cap layer system, having the steps of:

10 illuminating the free interface of a multilayer system with radiation in the extreme ultraviolet up to the soft x-ray wavelength region;

measuring the reflectance and the photoelectron current in an angularly resolved fashion;

15 determining the profile of the photoelectron current in the region of maximum reflectivity, and ascertaining therefrom a first phase shift of the intensity of the standing electromagnetic wave forming at the free interface; and

20 comparing with an already known photoelectron current profile with reference to a second phase shift of the corresponding standing electromagnetic wave at the free interface, and determining the difference in thickness by ascertaining the difference between the two phase shifts.

25 19. A method for determining the thickness of a cap layer system on the multilayer system from the phase shift of a standing electromagnetic wave in the extreme ultraviolet up to the soft x-ray wave region at the free interface of a multilayer system, having a cap layer system, having the steps of:

30 illuminating the free interface of a multilayer system with radiation in the extreme ultraviolet up to the soft x-ray wavelength region;

measuring the reflectance and the photoelectron current for specific combinations of wavelength and angular setting;

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determining the profile of the photoelectron current in the region of



maximum reflectivity, and ascertaining therefrom a first phase shift of the intensity of the standing electromagnetic wave forming at the free interface; and

5 comparing with an already known photoelectron current profile with reference to a second phase shift of the corresponding standing electromagnetic wave at the free interface, and determining the difference in thickness by ascertaining the difference between the two phase shifts.

10 20. A method for determining the thickness of a cap layer system on a multilayer system from the phase shift of a standing electromagnetic wave in the extreme ultraviolet up to the soft x-ray wave region at the free interface of a multilayer system, having a cap layer system, comprising the steps of

15 illuminating the free interface of a multilayer system with radiation in the extreme ultraviolet up to the soft x-ray wavelength region;

measuring the reflectance and the photoelectron current in a spectrally resolved fashion;

20 determining the profile of the photoelectron current in the region of maximum reflectance, and ascertaining therefrom the phase shift of the standing electromagnetic wave at the free interface; and

25 comparing the experimentally ascertained profile of the photoelectron current in the region of the maximum reflectivity with model calculations executed for various thicknesses of the cap layer system.

30 21. A method for determining the thickness of a cap layer system on a multilayer system from the phase shift of a standing electromagnetic wave in the extreme ultraviolet up to the soft x-ray wave region at the free interface of a multilayer system, having a cap layer system, comprising the steps of

35 illuminating the free interface of a multilayer system with radiation in the extreme ultraviolet up to the soft x-ray wavelength region;

measuring the reflectance and the photoelectron current in an angularly resolved fashion; and

5 determining the profile of the photoelectron current in the region of maximum reflectance, and ascertaining therefrom the phase shift of the standing electromagnetic wave at the free interface; and

10 comparing the experimentally ascertained profile of the photoelectron current in the region of the maximum reflectivity with model calculations executed for various thicknesses of the cap layer system.

22. A method for determining the thickness of a cap layer system on a multilayer system from the phase shift of a standing electromagnetic wave in the extreme ultraviolet up to the soft x-ray wave region at the free interface  
15 of a multilayer system, having a cap layer system, comprising the steps of

illuminating the free interface of a multilayer system with radiation in the extreme ultraviolet up to the soft x-ray wavelength region;

20 measuring the reflectance and the photoelectron current for specific combinations of wavelength and angular setting;

25 determining the profile of the photoelectron current in the region of maximum reflectance, and ascertaining therefrom the phase shift of the standing electromagnetic wave at the free interface; and

30 comparing the experimentally ascertained profile of the photoelectron current in the region of the maximum reflectivity with model calculations executed for various thicknesses of the cap layer system.

23. Method according to one of the claims 1 to 22 wherein all steps are carried out with spatial resolution.

35 24. Method according to one of the claims 1 to 23, wherein the measured data are furthermore compared with reference data measured on similar multilayer systems out of resonance.



25. Method according to one of the claims 1 to 24, wherein the measured data are compared with reference data obtained for specified multilayer systems.

5 26. An apparatus for carrying out methods as claimed in claims 1 to 25, having means for spatially and spectrally setting incident radiation, as well as a vacuum chamber in which a photon detector, a photoelectron detector and a sample holder are arranged, wherein an electrically conducting wide angle element is used as photoelectron detector and the means for spatially and  
10 spectrally setting incident radiation being optimized to provide a beam of narrow spectral band width and of small diameter.

27. An apparatus for carrying out methods as claimed in claims 1 to 25, having means for spatially and spectrally setting incident radiation, as well as a  
15 vacuum chamber in which a photon detector, a photoelectron detector and a sample holder are arranged, an electrically conducting wide angle element being used as photoelectron detector, and the means for spatially and spectrally setting incoming radiation being optimized to provide a beam of narrow spectral bandwidth of small diameter.

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28. The apparatus according to claim 26 or 27, wherein the sample holder has three translational degrees of freedom and three rotational degrees of freedom.

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29. The apparatus according to one of the claims 26 to 28, wherein a device is provided for applying an electric field in the vicinity of the sample.

30. The apparatus according to one of the claims 26 to 29, wherein a radiation source for extreme ultraviolet and/or soft x-ray radiation is present.

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31. The apparatus according to one of the claims 26 to 30, wherein at least two sample holders are provided together with means for connecting two or more samples in parallel and/or series with an amperemeter.

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32. EUV lithography apparatus comprising at least one photoelectron detector and at least one tuneable monochromator.

33. EUV lithography apparatus according to claim 32, wherein the incidence wavelength can be switched between an operating wavelength at which the lithography apparatus is operated during exposure and at least one useable wavelength which is used for qualifying optical elements arranged in the lithography apparatus.

34. EUV lithography apparatus according to claim 32, wherein the tuneable monochromator comprises a first reflective optical element comprising a first multilayer system with a maximum of reflectance at the operating wavelength and at least a second reflective optical element comprising a second multilayer system with a maximum of reflectance at the at least one useable wavelength, wherein the first and second reflective optical elements are preferably interchangeable with the operating reticle used for operating the lithography apparatus during exposure.

35. EUV lithography apparatus according to claim 34 wherein the wavelength assigned to the first and/or the second reflective optical element is determined by the given thickness of the layers of the first and/or the second multilayer system.

36. EUV lithography apparatus according to one of the claims 32 to 35 comprising at least one photoelectron detector and means for adjusting a residual gas atmosphere inside the EUV lithography device.

37. EUV lithography apparatus according to one of the claims 32 to 36 comprising a cleaning reticle.

38. EUV lithography apparatus according to one of the claims 32 to 37 comprising a collimator and/or at least one aperture for geometric beam shaping.

39. EUV lithography apparatus according to one of the claims 32 to 38 comprising means for generating local differences of partial pressures.

40. EUV lithography apparatus according to one of the claims 32 to 39 comprising a first photon detector for detection of photons at the operating wavelength and/or a second photon detector for detection of photons with lower photon energies corresponding to photon energies below about 90 eV, in particular photon energies below about 1.65 eV.

41. EUV lithography apparatus according to claim 40 wherein the second photon detector is a thermal imaging camera.

42. Method for operating of a EUV-lithography apparatus according to one of the claims 32 to 41, in which at predetermined times an irradiating operation is switched to a detection mode, in which

the photoelectron current and the reflectance is measured in dependence of the wavelength by tuning the monochromator;

the contamination state is identified by determination of the photoelectron current in the region of maximum reflectance and by comparison of the measured photoelectron current data with photoelectron current data modelled for different contamination states.

43. Method according to claim 42, wherein the residual gas atmosphere is modified in such a way that the contamination is reduced if control parameters of the contamination state are exceeded.

44. Method according to claim 42, wherein the composition of the residual gas atmosphere and the cross-section and position of the incident light beam are modified in such a way that material is deposited and/or removed at defined locations if control parameters of the contamination state are exceeded.

45. Method according to one of the claims 42 to 44, wherein the spectral and/or geometrical properties of the incident radiation are modified with the help of a cleaning reticle.

46. Method according to one of the claims 42 to 45, wherein the spatial and/or spectral properties of the incident radiation are modified by a collimator and/or at least one aperture.

5 47. Method according to one of the claims 42 to 46, wherein the partial pressures inside the lithography apparatus are modified at least in the irradiated region during the measurement and/or the deposition and/or the removal.

10 48. Method according to one of the claims 42 to 47, wherein the wavelength of the photons to be detected by the second photon detector are shifted to higher wavelengths by generating photons with specific wavelengths by controlling the standing electromagnetic wave being formed in the resonant case.

15 49. Reflective optical element for the extreme ultraviolet to soft x-ray wavelength range, in particular for use in an EUV-lithography apparatus according to one of the claims 32 to 41, comprising a multilayer system with a cap layer system, wherein the cap layer system is doped in such a way that at least  
20 part of the photons emitted from the reflective optical element are shifted to higher wavelengths than the operating wavelength, in particular to wavelengths in the infrared wavelength range.

25 50. Method for manufacturing an optical element comprising a substrate, a multilayer system and a cap layer system with a thickness distribution of the multilayer system and a thickness distribution of the cap layer system according to a given design

comprising the steps of

30 (i) coating the substrate with the multilayer system and the cap layer system using coating parameters;

35 (ii) illuminating the coated substrate in at least one surface point with said radiation having a wavelength and/or an incidence angle;

(iii) measuring a reflectance and a photoelectron current induced by radiation for various wavelengths and/or incidence angles resulting in a reflectance curve as a function of wavelength and/or incidence angle wherein said reflectance curve has a wavelength region and/or incidence angle region of maximum reflectance and in a photoelectron current curve as a function of wavelength and/or incidence angle wherein said photoelectron current curve has a profile within said wavelength region and/or incidence angle region of maximum reflectance;

(iii) determining the thickness distribution of the layers of the multilayer system and/or of the layers of the cap layer system on the coated substrate by comparing the measured reflectance curve and/or the photoelectron current curve in the wavelength region and/or incidence angle region of maximum reflectance with corresponding curves received from simulations for various thickness distributions of layers in the multilayer system and/or for various thickness distributions of the layers of the cap layer system.

51. Method according to claim 50, further comprising the step of

(iv) adjusting of the coating parameters and repeating the steps of claim 50 until the thickness distribution of the layers in the multilayer system and the thickness distribution of the cap layer system approximately coincides with the given design.

52. Method according to claim 50 or 51, wherein the thickness distribution of the cap layer system is constant across the whole surface of the mirror.

53. Method according to claim 50 or 51, wherein the thickness distribution of the cap layer system varies across the whole surface of the mirror.

54. Method according to one of the claims 50 to 53, wherein the wavelength of said radiation lies in the EUV range.

55. Reflective optical element for EUV radiation manufactured according to one of the claims 50 to 54.



56. EUV lithography apparatus comprising at least one optical element according to claim 55.

5 57. Reflective optical element for the EUV to soft x-ray wavelength range comprising a multilayer system and a cap layer system comprising at least one layer consisting of a transition metal or an alloy, a mixture or a compound comprising a transition metal, and being optimized with respect to a operation wavelength in the EUV or soft x-ray wavelength range,  
10 wherein at least one thickness of a layer of the multilayer system or of a layer of the cap layer system is chosen such that under irradiation with said operation wavelength a standing electromagnetic wave is formed in such a manner, that an intensity maximum of said standing electromagnetic wave is located in a range of the free interface of the reflective optical element.

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58. Reflective optical element according to claim 57, wherein the at least one layer or cap layer thickness is chosen such that the intensity maximum is located on the vacuum side of the free interface of the reflective optical element.

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59. Lithography apparatus comprising at least one reflective optical element according to one of the claims 57 or 58 and comprising a housing which can be evacuated and at least two inlets opening towards the reflective optical element which serve to supply an oxidizing gas or an oxidizing mixture of  
25 gases and a reductive gas or a reductive mixture of gases.

60. Method for operating a reflective optical element according to claim 57 or 58 in a closed system having a residual gas atmosphere comprising a hydrocarbon, water, and oxygen, in which as soon as irradiation with the  
30 operating wavelength is started the partial pressure of the hydrocarbon is increased such that carbon is deposited on top of and/or in the topmost layer, so that the intensity maximum of the standing electromagnetic wave is located in the range of the free interface.

35 61. Method according to claim 60, wherein the position of the intensity maximum with respect to the free interface is monitored by measuring the



photoelectron current and wherein the partial pressures of hydrocarbon, water and oxygen are readjusted in such a way, that the location of the intensity maximum relative to the free interface is controlled.

5 62. Method according to claim 61, wherein the partial pressures are readjusted in such a way that the intensity maximum is located on the free interface.

63. Method for operating a reflective optical element according to claim 57 or 58 in a closed system with a residual gas atmosphere comprising a reductive  
10 gas fraction and an oxidizing gas fraction, wherein the partial pressures of the gas fractions are adjusted in such a way that oxidative and reductive reactions at the topmost layer are in equilibrium.

64. Method according to claim 63, wherein a gas or a mixture of gases  
15 comprising oxygen atoms is used as an oxidizing gas fraction in the residual gas atmosphere.

65. Method according to claim 63 or 64, wherein at least one hydrocarbon is used as a reductive gas fraction in the residual gas atmosphere.  
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66. Method for operating a reflective optical element for the EUV to soft x-ray wavelength range comprising a multilayer system with a topmost layer comprising carbon and/or an oxide in a closed system with a residual gas atmosphere comprising a reductive gas fraction and an oxidizing gas  
25 fraction, in which the partial pressures of the gas fractions are adjusted such that oxidative and reductive reactions are in equilibrium.

67. Method according to claim 66, wherein a reflective optical element is used of which the thickness of at least one layer or cap layer is chosen such at least  
30 one layer thickness or cap layer thickness is chosen such that under irradiation with said operation wavelength a standing electromagnetic wave is formed in such a manner, that an intensity minimum of said standing electromagnetic wave is located in a range of the free interface of the reflective optical element.

68. Method according to claim 66 or 67, wherein a gas or a mixture of gases comprising oxygen atoms is used as an oxidizing gas fraction in the residual gas atmosphere.

5 69. Method according to one of the claims 66 to 68 wherein at least one hydrocarbon is used as a reductive gas fraction in the residual gas atmosphere.

10 70. EUV lithography apparatus with at least one reflective optical element for the EUV to soft x-ray wavelength range comprising a multilayer system with a topmost cap layer made of carbon and/or an oxide, in which at least the thickness of one layer or cap layer is chosen such that during irradiation at the operating wavelength a standing electromagnetic wave is formed in such a way that an intensity minimum is located in the area of the free interface of  
15 the optical element, with a housing that can be evacuated and in which the reflective optical element is arranged, and with at least two inlets which open towards the reflective optical element and are used for supplying an oxidizing gas or a mixture of gases and a reductive gas or a mixture of  
20 gases.